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Post-fire failure mechanisms of seawater-accelerated weathering composites for coastal and marine structures

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ABSTRACT

This paper is the first to examine the mechanical characteristics and the failure mechanisms of seawater-accelerated weathering GFRP composites followed by low intensity fire/heat damage. This work was done to understand how environmental conditions in a marine environment affected mechanical properties before and after low intensity fire damage. E-glass/vinylester composite specimens of angle-ply $[\pm 45^{\circ}/\text{mat}]_{2s}$ and cross-ply $[0/90^{\circ}]_{3s}$ used in marine and offshore applications were exposed and tested. The effect of fire-induced damage under low heat fluxes (10, 20, and 30 kW/m^2) on strength and modulus before and after 120 days of seawater exposure (freeze-thaw cycling in saline solution) is experimentally investigated. A total of 162 samples were tested for shear, tension, and compression. The fabric architectures and seawater exposure influence the post-fire residual properties. A time-dependent mechanical response (pre/post fire exposure) is also presented.

1. Introduction

Composite structures are increasingly being used in offshore oil and gas industry, marine vessels, seawalls structures, piers and many different buildings. Due to their inherent shear load demand, a variety of offshore, marine, and civil infrastructure applications, are usually constructed of double bias angle-ply [± 45°] or cross-ply [0/90°] fabric constructions. These structures are constructed of highly insulated lightweight sandwich wall panels and composite structural frame members. The monolithic laminates and face sheets are commonly made of reinforced woven roving or non-crimped knitted E-glass with fire retardant vinyl ester resin. The stiffness and strength of these structures depend mainly on the fiber and/or fiber-matrix interface. Like any construction materials, Fiber Reinforced Plastic composites (FRP) are susceptible to degradation due to severe environmental exposure. Composite structures in the marine environment (e.g., offshore oil and gas industry and seawalls structures, etc.) are considerably affected by saline seawater, salt-laden air, low/high temperature and possibly different fire intensities (heat exposure). Many researchers have severally discussed saline freeze-thaw exposure and fire-induced damage to composite structures. Relevant researches showed serious degradation in the mechanical properties after seawater exposure. Such findings reported that GFRP composites subjected to freeze-thaw exposure caused chemical and physical changes of matrix, fiber, and matrix-fiber interface leading to mechanical properties

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degradation [1]. Freeze-thaw exposure in saline solution caused crack opening and interfacial debonding due to the wicking and diffusion of NaCl solution [2]. These cracks lead to an increase of water absorption and consequently increase in matrix hydrolysis and plasticization [2–6], and eventually decrease the tensile properties of GFRP composites [7]. Moreover, the expansion of frozen water during freeze-thaw exposure affects the residual tensile strength of the fiber–matrix composites, initiates microcrack [2,8], increases the brittleness [9] and creates plies microbuckling damage in GFRP composites [10]. On the other hand, fire-induced damage to composite structures also caused chemical and physical changes including softening, decomposition, char oxidation, cracking, fiber–matrix interfacial debonding, delamination and fibers fusion [11,12] resulting in large reductions in the post-fire mechanical properties [13,14] due to thermal decomposition of the matrix [14,15]. Furthermore, it was found that the stiffness and strength of composite decrease significantly and rapidly once the temperature of the resin matrix exceeds the glass transition temperature [16–20]. It is important to note that for previous studies, medium intensity heat fluxes (50–75 kW/m^2) equivalent to compartment fires were used to study the composites properties during and after fire exposure. In such fire events, the composite properties are for all practical purposes fully lost, and the structure will fail, or, will need to be replaced after the fire. Studies have shown that residual tensile stiffness and strength were correlated to the measured mass loss [14,18] whereas the residual shear stiffness and strength correlated with the char thickness [13,14] and can be much lower than the original values [16]. Most of the experimental correlations and validations were based on unconditioned samples with no adjustments or knockdown factors to account for in-service conditions. No experimental characterization on the combined effect of seawater exposure and low intensity heat flux (10–30 kW/m^2) fire-induced damage to composite structures has been found in the literature. In the event of a fire, some composite materials will clearly be fully damaged and will lose all properties and would need to be replaced. However, for composites adjacent to the fire which may have encountered a lower heat flux due to distance from the heat source, the amount of actual damage that may occur is unknown. Perhaps after this low intensity heat flux exposure the composite may still be viable for use, and may not need to be replaced. An experimental investigation is needed to understand the failure mechanisms and to predict the residual mechanical properties of seawater-exposed laminates followed by low-intensity fire. The primary goal of this paper is to provide experimental knockdown factors for engineers to decide whether it is necessary to repair, replace or leave any offshore vinyl ester composite in the near field of a fire/heat source. This paper focused only on heat-damaged composite structures in the marine environment near fire-affected areas, not completely consumed/destroyed during a fire, and low fire intensity was therefore selected for this investigation. Using destructive/nondestructive evaluation techniques, this experimental work investigates the degradation and post-fire damage mechanism of double bias angle-ply $[\pm 45^{\circ}/\text{mat}]_{2s}$ and cross-ply $[0/90^{\circ}]_{3s}$ laminate constructions, before and after seawater exposure (freeze-thaw cycling in saline solution).

2. Experimentation

2.1. Materials and samples fabrication

Vacuum infusion molding process under high vacuum was used to mold all composite laminates. This process is generally used for large structural applications. The materials selected to manufacture the composite panels are shown in Table 1. Typical E-glass/vinyl ester with double bias $[+45/\text{-}45/\text{Mat}]_{2s}$ and cross-ply $[0/90]_{3s}$ fiber architectures were used in this study. The measured thicknesses of the laminates were 3.0 ± 0.1 mm (4 plies) for the double bias and 3.25 ± 0.1 mm (6 plies) for the cross-ply woven roving. The fiber volume fraction was around 54%. Panels were then cured for 30 days at room temperature (22.5 °C and 50% RH), then cut to specific ASTM test standards and prepared for environmental and mechanical testing, both for pre and post-fire mechanical testing (Table 2).

2.2. Seawater environmental exposure

A mixture of 3% NaCl and 97% distilled water by weight, was used for the saline solution to simulate the effect of chloride environmental condition caused by seawater. A temperature profile range from −20 °C to +40 °C was selected to accelerate the effect of aging degradation. Freeze-thaw exposure was conducted on 81 samples and was programmed for 120 days. Fig. 1a depicts the 24-h period of freeze-thaw cycling used in this study. Samples were fully submerged in a saline solution inside the stainless steel pans as shown in the below Fig. 1b. The freeze/thaw slab tester by Qualitest ™ (Model number EN 196–1) shown in Fig. 1b was used for the seawater environmental exposure. All seawater-exposed samples were removed from the environmental freeze-thaw chamber

Table 1
Materials selection and fabrication.

Samples	Fabric Construction/areal weight	Resin	Catalyst	Fibers Direction	Molding Process
EBXM1708	E-BXM-1708 E-Glass, 883 gr/m^2 total. [+45°(304 gr/m^2), −45°(304 gr/m^2), Chopped Mat (275 gr/m^2)] (Vectorply Corporation®)	DERAKANE 610 C-200 Epoxy Vinyl Ester Resin (Ashland Inc.)	1.25% Organic Peroxide, Cadox®	± 45°	VARTM Infusion with 28 Hg Vacuum Pressure
E-glass Plain Weave	E-glass 814 gr/m^2 (24 $oz./yd^2$) (Matrix Composites Inc.)			0/90°	